Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Materials & Molecular Research Division

To be presented at the Fourth International Conference on Mechanical Behaviour of Materials (ICM 4), Stockholm, Sweden, August 1983

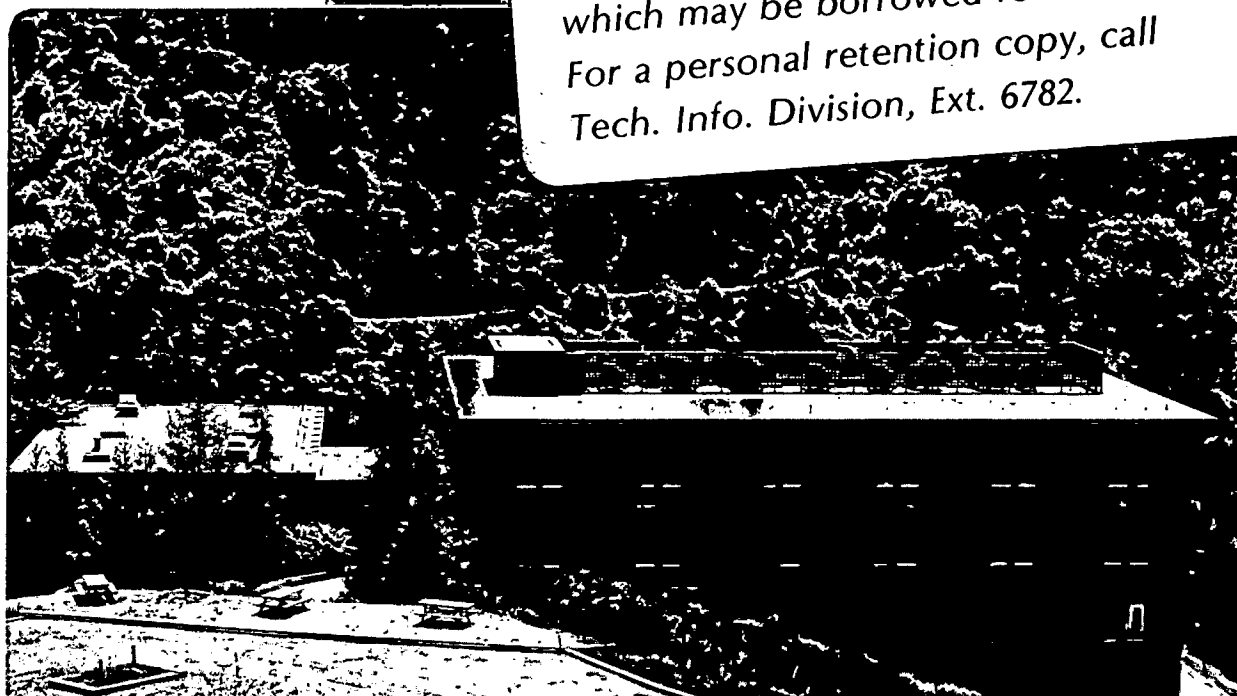FATIGUE CRACK PROPAGATION IN VISCOUS ENVIRONMENTS

J.L. Tzou, S. Suresh, and R.O. Ritchie

March 1983

DISCLAIMER

FATIGUE CRACK PROPAGATION IN VISCOUS ENVIRONMENTS

J. L. Tzou, S. Suresh and R. O. Ritchie

Materials and Molecular Research Division, Lawrence Berkeley Laboratory
and Department of Materials Science and Mineral Engineering,
University of California, Berkeley, CA 94720, U.S.A.

March 1983

FATIGUE CRACK PROPAGATION IN VISCOUS ENVIRONMENTS

J. L. Tzou, S. Suresh and R. O. Ritchie

Materials and Molecular Research Division, Lawrence Berkeley Laboratory
and Department of Materials Science and Mineral Engineering,
University of California, Berkeley, CA 94720, U.S.A.

ABSTRACT

The effect of dehumidified silicone and paraffin oils with viscosities from
5 to 60,000 cS, on fatigue crack propagation in a low alloy steel is examined
at both near-threshold ($\leq 10^{-6}$ mm/cycle) and higher ($\sim 10^{-6}$ to 10^{-3} mm/cycle)
growth rates. Results show that at low load ratios crack growth rates in oil
exceed those in moist air at near-threshold levels, whereas at higher growth
rates crack propagation in moist air is considerably faster than in oil.
Such observations are discussed in terms of three mechanisms specific to dry
oil environments: suppression of moisture-induced hydrogen embrittlement
and/or metal dissolution, minimization of oxide-induced crack closure and
hydrodynamic wedging effects of the viscous fluid within the crack.

INTRODUCTION

It is well recognized that the fatigue resistance of cyclically-stressed
components can be markedly affected by the presence of oil environments. For
example, early studies (Cordiano, Cochran, Wolfe, 1956) on rolling contact
fatigue indicated that the use of water-glycol based hydraulic fluids in
place of mineral oils could reduce bearing lives by up to 10%. In numerous
subsequent investigations, fatigue lifetimes have been reported to be in-
creased, decreased or unaffected by the presence of such apparently non-
corrosive fluids, for environments ranging from medicinal oils to synthetic
lubricants (Galvin, Naylor, 1965). Despite the lack of understanding of the
role of such environments, oils (particularly silicone oils) are regularly
used in fatigue studies to simulate reference inert environments or in multi-
axial fatigue testing to provide a medium for transmitting superimposed
hydrostatic pressure.

The objective of the present work is to examine mechanistically the role of
silicone and paraffin oils in influencing the fatigue behavior of a low alloy
steel. Specifically, the effect of dehumidified oils of viscosities ranging
from 5 to 60,000 cS is studied on rates of fatigue crack propagation, and
behavior compared with that for moist and dry gaseous atmospheres. It is
found that oil environments can lead to both faster or slower propagation

rates, compared to behavior in room air, depending upon oil chemistry, viscosity and principally the growth rate regime.

EXPERIMENTAL PROCEDURES

Tests were performed on a fully bainitic $2\frac{1}{4}$Cr-1Mo steel (ASTM A542 Class 3) of 500 MPa monotonic yield strength, 400 MPa cyclic yield strength, 610 MPa tensile strength and 77% reduction in area at room temperature. Fatigue crack propagation testing was conducted with 12.7 mm compact specimens (T-L orientation) cycled at 50 Hz frequency (sine wave) at load ratios (R = K_{min}/K_{max}) of 0.05 and 0.75, using d.c. electrical potential techniques to monitor crack length. Room temperature oil environments were provided by immersing the specimen in an enclosed oil bath. The oil was dehumidified by continuously bubbling dry helium gas and by maintaining a small positive pressure of helium within the system. Two types of oils were investigated, namely a series of chemically similar silicone oils (dimethyl polysiloxane) with kinematic viscosities of 5, 1000, 12,500 and 60,000 cS, and two paraffin oils (hydrocarbon mixtures) with viscosities of 25 and 75 cS.

RESULTS

The variation of fatigue crack propagation rates (da/dN) with stress intensity range ($\Delta K = K_{max} - K_{min}$) for A542-3 steel tested in the various oil environments is shown in Figs. 1-3. Results are compared with previously obtained data (Suresh, Zamiski, Ritchie, 1981) for this steel in room temperature moist air (30% relative humidity), dehumidified gaseous hydrogen (138 kPa pressure) and dehumidified gaseous helium (138 kPa pressure). In Fig. 1 where the low load ratio (R = 0.05) results for the silicone oils are plotted, it is apparent that crack growth rates in oil are *slower* than in air *above* $\sim 10^{-6}$ mm/cycle yet *faster* than in air at near-threshold levels *below* $\sim 10^{-6}$ mm/cycle. The near-threshold effect of oil is absent, however, at higher load ratios (R = 0.75) where threshold ΔK_0 values for both high and low viscosity oil environments as well as moist air and dry hydrogen atmospheres are virtually identical (Fig. 2). Similar low load ratio results were found for paraffin oils (Fig. 3), although the effect of these oils in enhancing growth rates at near-threshold levels and reducing growth rates above $\sim 10^{-6}$ mm/cycle was somewhat greater than in silicone oils. Also in Fig. 3 the highest and lowest viscosity silicone oils (5 and 60,000 cS) are compared with the two paraffin oils (25 and 75 cS) at R = 0.05. Above $\sim 10^{-6}$ mm/cycle the data for oils show the following trends: a) growth rates are faster at low load ratios with higher viscosities, b) growth rates in silicone oil are faster than those in paraffin oil and c) crack growth is slower in both oils than in air or hydrogen. The effect of viscosity on the value of the fatigue threshold ΔK_0 is negligible at R = 0.75 whereas at R = 0.05 there is a small but finite trend of decreasing ΔK_0 with increasing viscosity in both oils (Fig. 4).

Scanning electron microscopy of the samples tested in oil revealed fracture morphologies similar to that observed in room air, e.g., at near-threshold levels a fine-scale transgranular mode was seen with isolated evidence of intergranular facets (Fig. 5). The extent of fracture surface oxidation determined from Auger measurements, however, was quite different to that observed in gaseous environments (Fig. 6). Whereas the thickness of the near-threshold crack surface oxide layer (Fe_2O_3) reached 0.2 μm at R = 0.05 in moist air, measurements in both types of oil indicated oxide films which were only ~ 3 nm thick.

DISCUSSION

Similar to previous work (Suresh, Ritchie, 1982) on the role of gaseous and aqueous environments in influencing fatigue crack propagation in lower strength steels, it is clear from the present study that the effect of viscous environments is also markedly different at near-threshold as opposed to higher growth rates (i.e., below and above $\sim 10^{-6}$ mm/cycle, respectively). Specifically both dehumidified silicone and paraffin oils are shown to give rise to *faster* growth rates at near-threshold levels and *slower* growth rates above 10^{-6} mm/cycle, compared to crack growth in moist air at R = 0.05.

In general terms, such contrasting effects of environment have been rationalized in terms of a competition between two concurrent yet mutually competitive processes, namely corrosion fatigue mechanisms, e.g., hydrogen embrittlement and/or active path corrosion, which *increase* crack growth rates, and crack closure mechanisms, e.g., resulting from oxidation products at the crack tip (oxide-induced) or irregular fracture morphologies (roughness-induced), which *decrease* crack growth rates. Whereas corrosion fatigue mechanisms tend to dominate environmentally-influenced crack growth behavior at higher growth rates and at high load ratios, the role of closure mechanisms become increasingly more important at low load ratios as growth rates approach threshold levels (Suresh, Ritchie, 1982).

In the present study on viscous environments, the observed effects of dehumidified oils can be interpreted in terms of similar considerations, specifically involving three distinct mechanisms, i.e., i) exclusion of moisture from the crack tip thereby minimizing hydrogen embrittlement/metal dissolution processes, ii) exclusion of moisture and oxygen from crack tip thereby minimizing oxide-induced crack closure, and iii) partial penetration of the oil films within the crack to create additional closure from the hydrodynamic wedge effect of the viscous fluid. Since each of these mechanisms has a differing effect on crack growth rates depending upon the regime of crack propagation rate behavior, each mechanism is now discussed in turn.

Since both dry silicone and paraffin oils do not chemically react with steels, the principal function of such media is to act as inert environments for crack growth, as evidenced by the fact that their behavior is similar to that of dry gaseous helium (Figs. 1-3). Thus, the exclusion of moisture from the crack tip region, resulting from immersion in dehumidified oil, will minimize any enhancement in crack growth rates due to metal dissolution (oxidation) at the crack tip (Fig. 6) and/or hydrogen embrittlement from the consequent release of hydrogen. This reduced contribution to crack advance from corrosion fatigue processes will be effective over the entire range of growth rates and load ratios, but will dominate behavior above $\sim 10^{-6}$ mm/cycle since closure mechanisms here are ineffective. Thus it is to be expected that crack growth rates in oil in this regime will be slower than in moist air or hydrogen gas, and be comparable with rates in helium (Figs, 1,3). Similar explanations in terms of shielding the crack tip from detrimental environmental species have been used in the past to account for the reduction of crack growth rates in several alloys tested in inert liquid environments such as dodecyl alcohol, silicone oils and grease (Ryder, Martin, Abdullah, 1977).

For the current steel at the high cyclic frequencies tested, the exclusion of moisture and oxygen afforded by the oil environment has the reverse effect on crack growth rates at lower, near-threshold levels. As shown in Fig. 6, analysis of crack growth in moist air at low load ratios has revealed oxidation deposits on near-threshold fracture surfaces to be ~ 20-40 times larger than the naturally-occurring oxide thickness. Such oxide films result in

significant oxide-induced crack closure when they build up to thicknesses comparable with crack tip displacements. Accordingly, growth rates below $\sim 10^{-6}$ mm/cycle are progressively slower in moist environments at low load ratios due to an increasing influence of oxide-induced closure, since in this steel the near-threshold contribution to crack advance from corrosion fatigue processes is generally small at 50 Hz. The exclusion of moisture and oxygen to the crack tip in oil tests, however, results in minimal crack flank oxidation (Fig. 6) such that near-threshold growth rates in oil exceed those in moist air primarily due to a smaller influence of oxide-induced closure (Figs. 1-4). At high load ratios, however, where closure effects are minimal, growth rates in oil are almost identical to those in air (Fig. 2). The relative effect of oxide-induced crack closure on near-threshold growth rates in dry oil compared to moist air (at R = 0.05) can be appreciated by considering the simple model for such closure of a rigid wedge inside a linear elastic crack (Suresh, Parks, Ritchie, 1982). Here closure is modelled to reduce the stress intensity range from its nominal value ($\Delta K = K_{max} - K_{min}$) to some near tip effective value ($\Delta K_{eff} = K_{max} - K_{cl}$), where K_{cl} the closure stress intensity is given in terms of the maximum oxide wedge thickness d located at distance 2ℓ behind the crack tip and the elastic modulus in plane strain E' (Tada, Paris, Irwin, 1973):

$$K_{cl} \approx \frac{d \, E'}{4\sqrt{\pi \ell}} \quad . \tag{1}$$

Taking $\ell \sim 2$ μm (Suresh, Parks, Ritchie, 1982), the maximum excess oxide (d) in moist air close to ΔK_0 is ~ 0.2 μm compared to ~ 3 nm in oil (Fig. 6). From Eq. (1) the corresponding values of K_{cl} at R = 0.05 are ~ 4.5 MPa$\sqrt{m}$ in air and less than 0.1 MPa$\sqrt{m}$ in oil, clearly showing that the driving force for crack extension in oil is far less restricted by oxide-induced closure.

Both protective effects provided by the oil environments described above are essentially independent of oil chemistry and viscosity, provided of course the oil is chemically inert. However, the current results in Figs. 1-4 indicate growth rates to be marginally higher in the higher viscosity oils at both near-threshold (R = 0.05) and higher growth rates. Moreover, at comparable viscosities, paraffin oils showed the faster growth rates near ΔK_0 and the slower growth rates above $\sim 10^{-6}$ mm/cycle (at R = 0.05). Such observations can be rationalized by considering the extent of penetration of the oil films into the crack and the resultant closure which arises due to the hydrodynamic wedge effect of the viscous fluid (Endo, Okada, Hariya, 1972). The penetration of the oil is governed by the capillary action of the crack walls and related to the physical properties of the oil (notably the viscosity, surface tension, wetting angle, etc.). The subsequent total hydrodynamic pressure generated by such an oil is then given by (Endo and coworkers, 1972):

$$p = -\frac{6\eta \, x^4}{h^3} \frac{d\theta}{dt} \quad , \tag{2}$$

where h is the crack mouth displacement, $d\theta/dt$ the angular closing velocity of the crack walls, η the absolute viscosity and x the penetration depth ($\propto \eta^{-1}$). Using superposition methods, the linear elastic stress intensity resulting from such pressure (K_p) is directly proportional to p, such that at constant frequency, crack length and stress amplitude, K_p will be proportional to the fourth power of the penetration distance. However, as x is dependent upon η^{-1}, K_p will be governed by the inverse third power of viscosity. Since paraffin oils wet steel, the penetration of these fluids into the crack is

far more effective than for silicone oils. In fact, based on experimental observations and consideration of the above analyses (Tzou, Suresh, Ritchie, 1983), it appears that oil film penetration is minimal at 50 Hz at near-threshold growth rates, particularly for the 1000 to 60,000 cS viscosity oils, such that crack closure induced by oil pressure at these levels is relatively insignificant. At higher growth rates, on the other hand, although penetration into the crack is still restricted for the higher viscosity oils (at R = 0.05) due to the small crack mouth displacements, partial oil penetration into the crack can result in additional crack closure for oils of lower viscosity. Accordingly, crack growth rates between $\sim 10^{-6}$ to 10^{-5} mm/cycle in the paraffin oils (Figs. 3 and 4) and in the 5 cS silicone oil (Fig. 4) were actually slower than in dehumidified helium gas indicating that both environmental shielding and viscous fluid-induced closure mechanisms were active. Thus, effects of oil chemistry and viscosity on fatigue crack propagation behavior can be rationalized in terms of corrosion fatigue processes, crack closure and hydrodynamic wedging. However, whereas closure induced by corrosion debris is significant at near-threshold levels, for the frequencies and oils tested, closure induced by viscous oil pressure is only relevant at higher growth rates.

CONCLUSIONS

Silicone and paraffin oils are shown to have significant but opposite effects on fatigue crack growth behavior of A542-3 steel above and below 10^{-6} mm/cycle. In the near-threshold region ($< 10^{-6}$ mm/cycle), crack growth rates at low load ratios are *higher* and threshold ΔK_0 values lower in oil than in moist air although little effect is seen at high load ratios. There is a small but finite decrease in ΔK_0 with increasing viscosities. At higher growth rates (10^{-6} to 10^{-3} mm/cycle), growth rates in oil are *lower* than those in moist air or dry hydrogen, with the lowest viscosity and paraffin oils showing the slowest rates. Such complex crack growth characteristics in dry viscous environments can be rationalized in terms of three mutually competitive mechanisms: suppression of corrosion fatigue processes, minimization of oxide-induced closure and development of a wedging action of the oil due to partial penetration within the crack.

ACKNOWLEDGMENTS

REFERENCES

Cordiano, H. V., E. P. Cochran, and R. J. Wolfe (1956). A study of combustion resistant hydraulic fluids as ball bearing lubricants. Lubric. Engng., 12, 261-274.

Endo, K., T. Okada, and T. Hariya (1972). Fatigue crack propagation in bearing metals lining on steel plates in lubricating oil. Bull. JSME, 15, 439-445.

Endo, K., T. Okada, K. Komai, and M. Kiyota (1972). Fatigue crack propagation of steel in oil. Bull. JSME, 15, 1316-1323.

Galvin, G. D., and H. Naylor (1965). Effect of lubricants on the fatigue of steel and other metals. Proc. Instn. Mech. Engrs., 179, 857-875.

Ryder, D. A., M. Martin, and M. Abdullah (1977). Some factors influencing stage I fatigue-crack growth. Metal Science, 11, 340-344.

Suresh, S., and R. O. Ritchie (1982). Mechanistic dissimilarities between environmentally-influenced fatigue crack propagation at near-threshold and higher growth rates. Metal Science, 16, 529-538.

Suresh, S., D. M. Parks, and R. O. Ritchie (1982). Crack tip oxide formation and its influence on fatigue thresholds. In J. Bäcklund (Ed.), Fatigue Thresholds, Vol. 1, EMAS Ltd., Warley. pp. 391-408.

Suresh, S., G. F. Zamiski, and R. O. Ritchie (1981). Oxide-induced crack closure: An explanation for near-threshold corrosion fatigue behavior. Metall. Trans. A, 12A, 1435-1443.

Tada, H., P. C. Paris, and G. R. Irwin (1973). In Stress Analysis of Cracks Handbook, Del Research Corp., Hellertown, PA.

Tzou, J. L., S. Suresh, and R. O. Ritchie (1983). Role of oil chemistry and viscosity in influencing fatigue crack propagation in viscous fluids. Metall. Trans. A, submitted to.
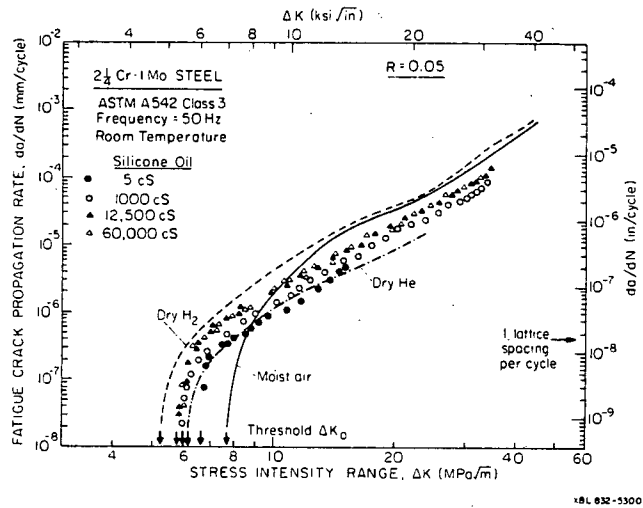
Fig. 1. Fatigue crack growth behavior in silicone oils
(5-60,000 cS viscosities) at R = 0.05 compared
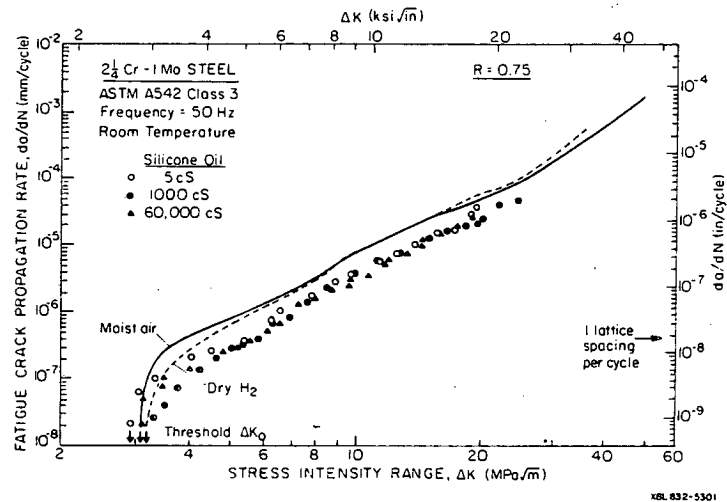to data for moist air and dry gaseous hydrogen
and helium.

Fig. 2.   Fatigue crack growth behavior in silicone oils
          (5-60,000 cS viscosities) at R = 0.75 compared
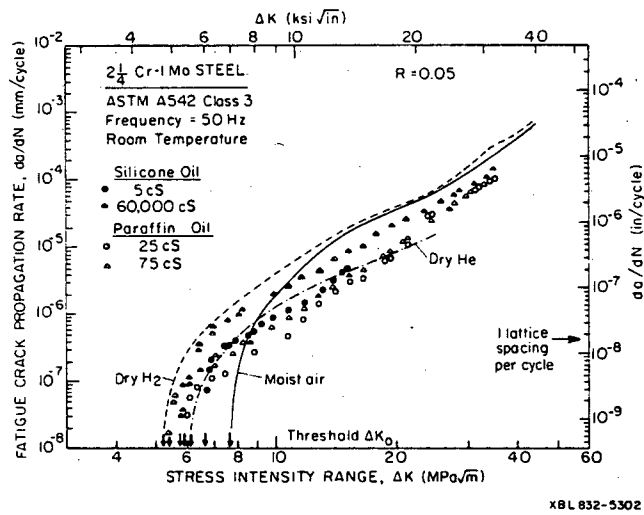   to data for moist air and dry gaseous hydrogen.

Fig. 3. Comparison of fatigue crack propagation behavior
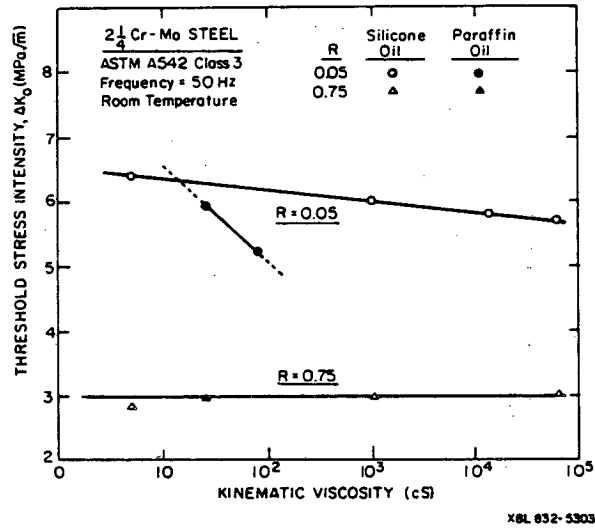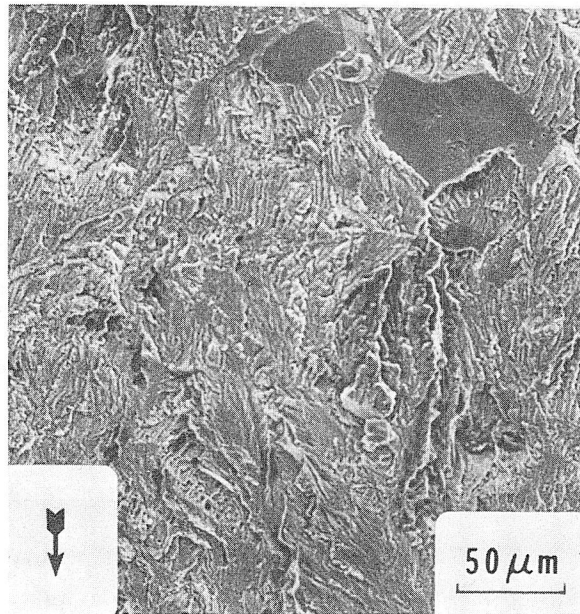at R = 0.05 in high and low viscosity silicone
and paraffin oils.

Fig. 4. Variation of threshold stress intensity range
(ΔK_0) at R = 0.05 and 0.75 with kinematic
viscosity for silicone and paraffin oils.

XBB 832-1568

Fig. 5. Fractography of near-threshold fatigue in oil,
showing fracture surface in 25 cS paraffin oil
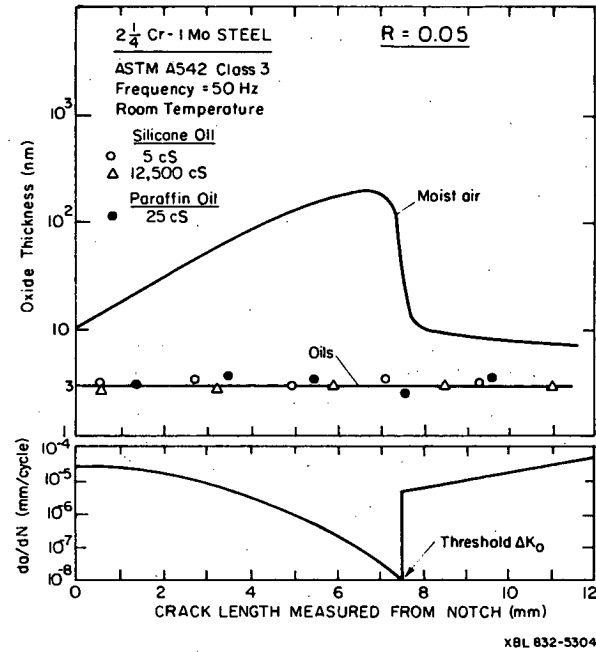at $\Delta K \approx 6.0$ MPa$\sqrt{m}$ (R = 0.05). Arrow indicates
crack growth direction.

Fig. 6. Variation in thickness of crack surface oxide
debris with crack length and growth rate for
oil environments compared to previous results
in moist air.